Chapter 3
An ERA Acute Model Overview

Abstract ERA Acute is a model for environmental risk assessment of acute discharges. The calculations follow a common framework for all environmental compartments, whilst maintaining the mechanistic integrity of each compartment and/or VEC group, by using compartment-specific inputs of oil exposure and VEC-specific geographical distribution, vulnerability and recovery-defining parameters/functions. The method allows for using three different levels of detailing in VEC in the exposure and impact calculations. For the highest level of detail, a second step calculates recovery times in three time-factors, as well as the ERA Acute-specific RDF which combines the extent of impact and recovery. The continuous functions of impact and recovery calculations are presented in this chapter, separately for all four compartments. All data are calculated in grid cells, facilitating the use of GIS for viewing inputs and results. The methodology adds up impacts from grid cells to populations, and calculates result statistics from single simulations to scenarios, to multi-scenario DSHAs and cases.

Keywords Environmental risk assessment · Oil spill risk assessment · ERA Acute risk functions · ERA Acute impact · ERA Acute restoration · Resource Damage Factor

3.1 Setting up the Case and Input to Exposure Calculations

Cases and DSHAs that are analyzed in ERA Acute can consist of one or several spill scenarios, each with a different spill rate, duration, depth (location), and probability distributions, set up in a rate-duration matrix. A DSHA can occur with a frequency, usually determined by historic spill statistics. Each oil spill scenario is modelled with multiple stochastic simulations, covering different simulation periods (start dates) and therefore representing different results of possible distribution of oil. The conceptual build-up of an analysis-case is described in Chap. 1, see also Figs. 1.5 and 1.6.

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A rate-duration matrix including the probability distribution between rate (groups) and duration intervals can have different forms and detail, depending on the input given. A fictive, simplified example from a multi-scenario blowout-DSHA is presented in Table 3.1 and the frequency distribution is illustrated in Fig. 3.1. As a simplified alternative to the multi-scenario assessment, the DSHA could alternatively be a single scenario oil spill modelling restricted to one (weighted) oil spill rate and duration (100% rate probability). The DSHA frequency of a blowout from the example exploration drilling is 1.2×10^{-4}.

Each combination of rate and duration is run as a set of many simulations in oil spill trajectory modelling, given as inputs to ERA Acute for calculating exposure. The oil spill model results file must list results of each single simulation in the scenario, and must contain the following information for each grid cell:

- Sea surface: Oil film thickness, oil coverage and duration of exposure.
- Shoreline: stranded oil amounts.
- Water column: Concentration of total hydrocarbon content (THC_{max}) in the water column or potential mortality % if available from the oil drift model (see 3.6.1).
- Seafloor: Oil amounts on the seafloor.

Oil spill trajectory data are exported to the same grid as used for the VEC data and the connection between the two data types is the cell ID. VEC data and the additional input data needed for the exposure calculations are described for each compartment in the sections below.

3.2 Impact and Restoration Modelling

Calculations of damage are carried out in two main steps comprised of several substeps (Fig. 3.2). Step (A) calculates the magnitude/extent of the impact and Step B calculates the duration of the impact. Three time-factors are calculated from impact to recovery of the impacted VEC (see Fig. 3.2). The basic framework of the calculations is common between the compartments, including many of the general summaries of risks across cells, simulations and scenarios. However, compartments and/or VECs can be impacted and restored through different mechanisms of action and regrowth, as described in the compartment development reports (Bjørgesæter and Damsgaard Jensen 2015; Brude et al. 2015; Brönner and Nordtug 2015; Brönner et al. 2015, 2017; Stephansen et al. 2015, 2017a, b). Calculations of lethality and recovery time factors are therefore different between compartments. The common framework is described in this section.

3.2.1 Step A: Impact Modelling

All compartments build on the same general methodology framework for the basic impact calculation for a cell and simulation at step A; incorporating probability of

Table 3.1 Example of a rate-duration matrix where each combination of rate and duration makes up a scenario

Release point	Probability release point	Spill rate (Sm^3/day)	Rate probability	Duration (days) and probability distribution					
				2	5	15	35	55	70
Surface	0.1	1500	0.6	0.5	0.2	0.15	0.05	0.08	0.02
		3000	0.35						
		8000	0.05						
Seabed	0.9	1000	0.6	0.4	0.2	0.18	0.07	0.12	0.03
		4000	0.35						
		7000	0.05						

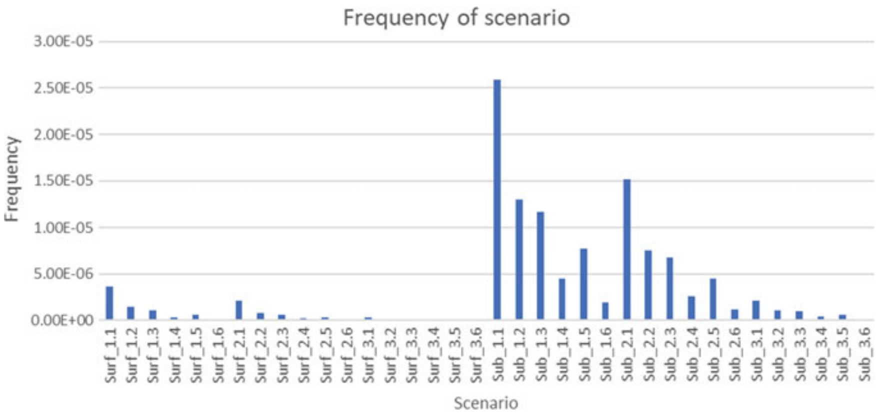

Fig. 3.1 Frequencies of each scenario from Table 3.1, where Surf = Surface spills, first digit represents the rate and second digit represents the duration. The sum of the frequency contributions is the DSHA frequency, 1.2×10^{-4}

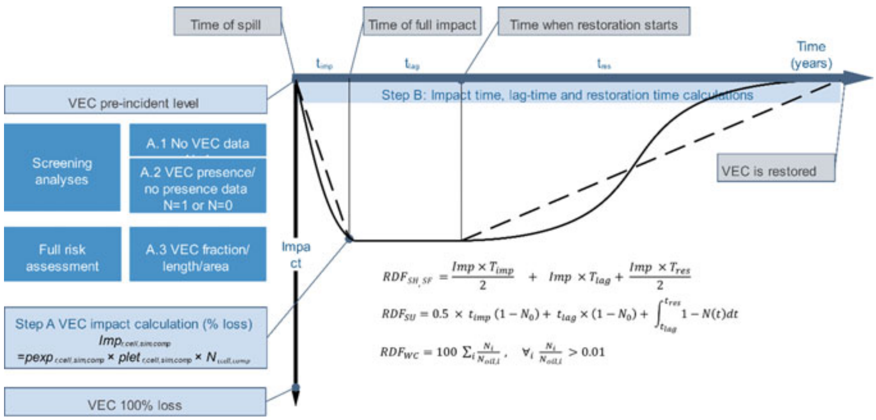

Fig. 3.2 Illustration of the impact (population/community loss) and restoration modelling in ERA Acute following a spill. Impact-, lag- and restoration times are defined along the time axis. The curve illustrates the initial steep decline in impacted resource, the increase in impact slows down until full impact is reached. Impact magnitude is at its maximum until restoration can start, which is illustrated by a re-growth curve. The area formed by the curve and timeline is the total combined expression of the impact extent and duration (surface) and water column compartments and simplified (dashed lines) for shoreline and seafloor

exposure, probability of lethal effect given exposure and abundance of vulnerable resources (Eq. 3.1) (Spikkerud et al. 2006 (Background Report 1)).

$$\mathrm{Imp}_{sim,cell,comp,VEC,month} = \mathrm{pexp}_{sim,cell,comp,VEC} \times \mathrm{plet}_{sim,cell,comp,VEC} \times N_{VEC,cell,comp,month} \tag{3.1}$$

where:

- *pexp*: Probability that the exposure will occur
- *plet*: Probability of lethal effect at the given exposure
- *N*: VEC unit in the grid cell. Population fraction (for sea surface and water column) km coastline (for shoreline types) or km^2 (for seafloor habitats).
- The calculation is carried out for each *Sim* (simulation), *cell*, *comp* (compartment) and for each *VEC*.

For each compartment and resource, the impact *Imp* is calculated for each grid cell in each simulation. For the month(s) that are covered by the oil spill simulation, results are reported in the cells with exposure to the VEC that has abundance above zero in the cell in the given month.

Although the impact calculations follow the same basic framework of Eq. 3.1, the functions used for calculating the factors *pexp* and *plet* values are different in the four compartments, reflecting that exposure routes and mechanisms of lethal action are different in the four compartments as well as between different resources and/or resource groups. Each compartment uses different relevant oil drift simulation input parameters in the exposure calculations.

As stated in the basic principles in Chap. 1, ERA Acute provides the opportunity to use different levels of detailing based on availability of resource data (see Figs. 3.2 and 3.3).

- Level A.1: If VEC data are omitted, ERA Acute assumes that sensitive resources are present in all cells in the analysis area ($N = 1$, ref Eq. 3.1), thus impact is dependent on exposure and lethality calculations for each cell.
- Level A.2: If the data sets are available in polygons with data on presence or no presence of biological resource data ($N = 1$ or $N = 0$, ref Eq. 3.1). Compared to A1, A2 will calculate impact only in cells where resources are present, eliminating cells with no presence.
- Level A.3: Fraction of VEC population present in the cell, adding up to $N = 1$ (100%) over all cells for sea surface and water column, length of coastal VEC type for shoreline or area of seafloor habitat. This level will provide an impact assessment of the total fraction of the population lost or total shoreline or seafloor impact. The data adaption (N-value) will directly affect the numerical value of the result and comparisons between compartments must be used with caution.

3.2.2 Step B: Impact Duration Modelling

The duration of the impact is calculated in step B, where the following time factors are defined:

- Impact time (t_{imp}), the time from the spill until full impact is seen (usually set to 1 year for a full annual cycle)
- Lag-time (t_{lag}), the time from full impact until recovery can start (where relevant)

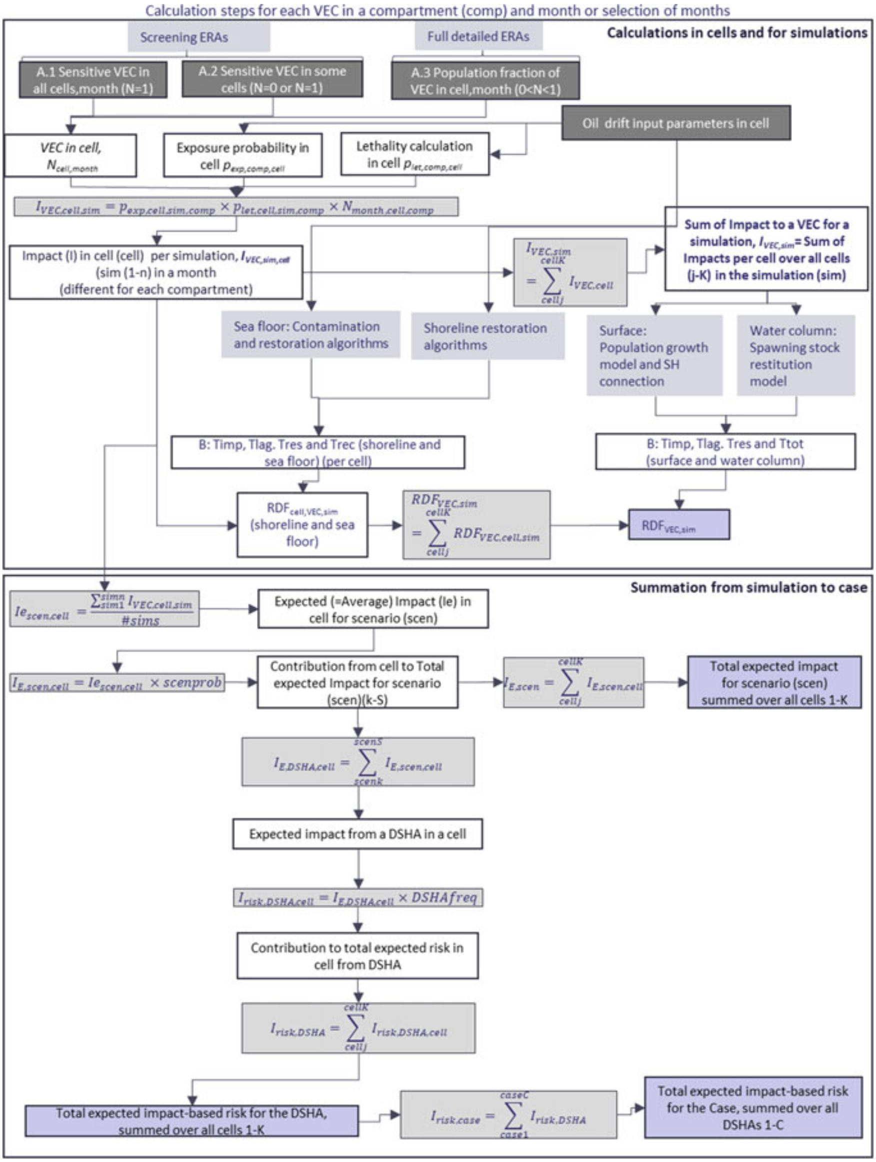

Fig. 3.3 Illustration of the impact and restoration calculations in cells and summations over all cells. Calculations in single cells and simulations (upper section) provide the most detailed options for result analysis of scenario results, whereas the summary steps from initial calculation of impact in a cell for a simulation to the sum of total expected impact for a DSHA gives results for multi-scenario DSHAs and cases. The illustration shows that many levels of calculations may be extracted and presented. (scenprob = probability for scenario, dshafreq = frequency for the DSHA)

- Restoration time (t_{res}), the re-growth time from restoration starts until the VEC is recovered.
- Recovery time (t_{rec}), the sum of the three time-factors is the total time from spill to recovered VEC.

In nature, there is no clear distinction between the time phases, as inhibition of growth and re-growth can happen simultaneously, depending on the resource in question. Much of the researched literature on restoration following historic spills do not discriminate between lag- and restoration phase (see reference lists in the background reports). However, ERA Acute offers the possibility if more knowledge exists, for the user to make an expert judgement of the division between these parameters in the input, for example if there is a known threshold for recovery. For the four compartments, different parameters and sub-models are used to calculate restoration times.

3.2.3 The Two Steps Together and the Resource Damage Factor

Figure 3.2 builds on Fig. 1.2 and illustrates how impact (population/community loss) and recovery modelling in ERA Acute have been implemented, and where within the framework the formulas are used. Impact-, lag- and restoration times are defined along the time axis. The curve illustrates the initial steep decline in impacted resource from pre-spill status, until full impact (*Imp*) is reached after t_{imp}. Impact magnitude is at its maximum until restoration can start after $t_{imp} + t_{lag}$, which is illustrated by a re-growth curve to restored status of the VEC. The area formed by the curve and timeline is the total of the impact extent and duration, as also proposed by Lein et al. (1992). Restoration modelling to determine the time factors in ERA Acute reflects different restoration mechanisms in individual compartments and/or resource groups.

For sea surface and water column, restoration modelling enables an integral function for the calculation of the geometrical area that represents the combined expression of damage extent and duration. This combined expression is called the *Resource Damage Factor* (RDF) in ERA Acute (Eq. 3.5 (for surface) and Eq. 3.17 (water column)). This factor is in line with the approach used in the NRDA for the Deepwater Horizon incident to calculate "cetacean-loss-years" (Deepwater Horizon Natural Resource Damage Assessment Trustees 2016). A simpler approach has been proposed and implemented for seafloor and shoreline to calculate the RDF. Based on the total impact to a community, and including the duration of the impact, lag and restoration times, the RDF for shoreline and seafloor is calculated using linearized expressions of decline and re-growth, given in the compartment-specific sections below (Eq. 3.9 (shoreline and seafloor)). The different formulas for calculating RDF are summarized in Fig. 3.2).

3.3 Surface Compartment Calculations

The VEC unit (N) in the sea surface compartment is a population characterized by (1) population density, (2) population distribution and (3) population size. The values in the cells are fractions (relative abundances) of the population. Seabirds, marine (or aquatic) mammals and sea turtles are assigned to different wildlife groups depending on the species characteristics related to their *individual vulnerability* to oiling (physiological sensitivity to oil) and *population vulnerability* (factors affecting the potential rate of growth and long-term population size) (Bjørgesæter and Damsgaard Jensen 2015).

3.3.1 Impact Modelling

The main impact to surface VECs is through physical contact with surface oil with subsequent effect on feather structure, insulation and buoyancy, ingestion of oil, aspiration and absorption of oil components (e.g. Deepwater Horizon Natural Resource Damage Assessment Trustees 2016; National Research Council (US) 2003). The proposed threshold levels for lethal oil film thickness (2 μm for seabirds and 10 μm for marine mammals/turtles) are derived from existing literature (Hughes et al. 1990; Jenssen and Ekker (1989, 1991a, b), Jenssen 1994; Koops et al. 2004; O'Hara and Morandin 2010; Peakall et al. 1985; Scholten et al. 1996; Stephenson 1997), different environmental risk analyses methods (French-McCay 2004, 2009; NOROG 2007; Spikkerud et al. 2006) and peer group discussions. In their comparative risk assessments as input to a relative risk methodology, Bock et al. (2018) used a lower threshold of 10 μm and an upper threshold of 100 μm.

The impact for surface VECs in a cell is proportional to the fraction of the cell covered with oil above the threshold thickness of oil and the period with harmful oil in the cell, adjusted by two individual species/species group-specific vulnerability factors (behavioral and physiological factor s); p_{beh} and p_{phy} (See Supplementary Information, Tables 1 and 2). The factors represent the likelihood of being oiled and the likelihood of lethal effect given exposure, respectively and are derived for 13 wildlife groups and 58 species based on different oil vulnerability indexes (OVI). The fraction of VEC impacted (denoted N_{let}) is calculated for the relative abundance of a defined population (N) in a grid cell i and the calculations are summarized as follows (Eq. 3.2).

$$N_{let} = \sum_{i=1}^{n} N_i - \left(1 - p_{beh} \times Cov_{TH} \times p_{phy}\right)^{T_{\exp TH}} \times N_i \tag{3.2}$$

where:

- TH is oil film thickness threshold level
- Cov is the fraction of a cell covered with oil thicker than TH

- T_{exp} is exposure time of oil thicker than TH
- p_{beh} is the probability of encountering an area with surface oil (sea surface)
- p_{phy} is the probability of lethal effects given encountering with oil above TH

An alternative equation has been derived for oil drift models that do not estimate the exposure time. This equation will result in lower impact than (Eq. 3.2) if T_{exp} > 1 day and it is therefore recommended to use an oil drift model that estimates exposure time in the cell.

3.3.2 Time Factors and Recovery Modelling

The impact time in sea surface is set to 1 year, i.e. full impact is expected to be seen within one annual cycle including a breeding season. Contamination of shoreline habitats and breeding sites used by the surface VECs may have long-term consequences that may inhibit or prolong the recovery of the population, e.g. following the Deepwater Horizon incident (In ERA Acute, this is incorporated by using the lag-time calculated in the shoreline compartment ($t_{lag,sh}$ Natural Resource Damage Assessment Trustees 2016; National Research Council (US) 2003), the relative abundance data of the species in habitats (N_{hab}) and a resource-specific sensitivity factor (SF_r) for the resource (r). The calculations are summarized in Eq. 3.3.

$$t_{lag,su} = \sum_{i=1}^{\infty} N_{hab_i} \times t_{lag,sh_i} \times SF_r \tag{3.3}$$

The restoration time is calculated based on the population loss from Eq. 3.2, using a discrete logistic growth model (Maynard-Smith and Slatkin 1973). The model estimates the relative population size N in generation t + 1 as a function of the number of individuals in the previous generation. A generic look-up table of the fundamental net reproductive rate (R) for seven wildlife groups is used to determine the growth rate and the vulnerability of the population. See Supplementary Information 1 Table 3 which includes references for the values.

$$N_{t+1} = \frac{N_t R}{1 + (aN_t)^b} \tag{3.4}$$

- R = the fundamental net reproductive rate.
- $a = (R–1)/K$, where K is the carrying capacity
- b = a factor determining the density dependence type.

The restoration time factor is defined as the period from restoration starts until the population is restored to a pre-defined level of its pre-spill baseline.

The total recovery time (t_{rec}) is the sum of impact (t_{imp}), lag (t_{lag}) and restoration time (t_{res}). Together with RDF_{su} for the sea surface it is illustrated in Fig. 3.2. For the sea surface compartment, the RDF_{SU} is calculated by Eq. 3.5:

$$RDF_{SU} = 0.5 \times t_{imp}(1 - N_0) + t_{lag} \times (1 - N_0) + \int_{t_{lag}}^{t_{res}} 1 - N(t)dt \tag{3.5}$$

where:

- t_{imp}: *Impact time*. Time until full impact is observed. This value is set to 1 year as most acute impacts are assumed to be apparent after 1 reproductive year cycle.
- t_{lag}: *Lag-time*. Time until contamination has been reduced sufficiently for restoration to begin.
- t_{res}: *Restoration time*. The time from restoration starts until the population/community is restored to a pre-defined level of its pre-spill status or equivalent threshold.
- N_0 is impacted population.

3.4 Shoreline Compartment

3.4.1 Impact Modelling

The shoreline impact modelling uses input from an established shoreline habitat classification ranking system, the Environmental Sensitivity Index (ESI) shoreline ranking (NOAA 2002) for each grid cell in the assessment area. The VEC input (*N*-value) to impact calculation in the shoreline compartment is the number of kilometers shoreline of a particular ESI shoreline ranking in a cell (Brude et al. 2015). The ESI classification scheme (NOAA 2002) is based on the physical and biological characteristics of the shoreline environment and factors influencing the sensitivity to oil contamination, such as shoreline slope, exposure to waves and tidal energy, substrate type, biological sensitivity restoration time and ease of cleanup. Shoreline segments with higher rankings are more sensitive, following a collective evaluation of several factors contributing to vulnerability towards oil. Segments with higher rankings are therefore more likely to be damaged by oiling. Some species may be relevant to assign as a shoreline VEC in particular life stages, but then it is the habitat that is the VEC. For example, for areas where this is relevant, turtle nesting beaches may be included as a sub-group of ESI-rank 3A, although adult turtles are exposed to oil at the surface and are a VEC in that compartment.

Based on input of data for accumulated oil on the shoreline from oil drift simulations and user-defined oil density, the volume of oil in the different ESI habitats (V_r) in the grid cell is estimated by weighting the various ESI segments by their length and by applying the Oil-Holding Capacity (OHC) (Etkin et al. 2007) related to each ESI ranking (See Brude et al. 2015 for equations). The slope associated with each ESI ranking (see NOAA 2002), the tidal range and a patchiness factor originally set at 0.2, derived from a collective assessment of the shoreline oiling of the Deepwater Horizon and Exxon Valdez oil spills (described in Brude et al. 2015) and calibrated to 0.3 in 2020 (DNV GL, Akvaplan-niva and Acona 2020), is used to calculate the impacted width (W_{imp}) of the oiled shore in each segment.

Samaras et al. (2014) used tidal range (TR) and beach slope (sl) in order to define the width of the impacted coastal zone (W_{imp}) by:

$$W_{imp,r} = \frac{\mathrm{TR}}{\sin(\mathrm{atan}\,sl)} \times 0.3 \tag{3.6}$$

The oil film thickness (T) for each ESI segment is then calculated by:

$$T_r = \frac{V_r}{L_r \times W_{imp,r}} \tag{3.7}$$

where V_r is the amount of oil stranded and L_r is the length of the shoreline (segment of ESI ranking). The total impact for each ESI ranking is then given by the total length (L) for all grid cells where the thickness is above the lethal threshold value (TH). TH used in ERA Acute is 1 mm for vegetation (herbaceous plants and trees) on ESI categories 8–10, and 0.1 mm (100 μm) for invertebrate *epifauna* living in intertidal habitats on hard substrates (based on a review by French-McCay 2009). In a recent study, Bock et al. (2018) used 100 μm (lower)/1 mm (upper for vegetation) and 10 μm (lower)/100 μm (upper) for intertidal invertebrates.

$$Imp_r = \sum_{cell} L_r | T_r \geq TH \tag{3.8}$$

3.4.2 Time Factors and Recovery Modelling

Experience from shoreline oiling after the Deepwater Horizon Oil Spill (DHOS) also illustrate how erosion and depositional processes of the beach cycle, seasonal wind pattern and storms to a large extent impact how oil became buried, exposed and remobilized (Michel et al. 2013). Oil is removed by natural processes (or clean-up) until the shoreline is eligible for recovery and recolonization of species. The lag phase (t_{lag}) of a shoreline after oiling can be defined as the period of oil thickness above the effect-threshold value. It is influenced by volume, oil type and weathering state, shoreline hydrodynamic energy level, OHC and intrinsic oil degradation processes. Due to the more rapid removal of oil from shorelines with high wave energy, a separate lag-phase in the damage expression is considered to be relevant for medium and low energy shorelines, while the recovery time for high energy shorelines can be based on the length of the restoration phase only. A look-up table based on hydrodynamic energy level in combination with oil type specific impacts is implemented as outlined in Table 3.2.

Table 3.2 Lag-times in shoreline types classified by energy level and main oil characteristics

Shoreline energy status (ESI)	t_{lag} (years)	Type 1 very light oils	Type 2 light oils	Type 3 medium oils	Type 4 heavy oils
High energy (ESI 1A-2B)	–	0	0	0	0
Medium energy (ESI 3A-7)	0–1	0	0	1	1
Low energy (ESI 8A-10E)	3–10	0	3	7	10

The restoration phase is defined as the period from when oiling is below the effect threshold value until vegetation and invertebrates have reached 99% of the pre-spill function. Recovery rates for shorelines after damage by oiling for modelling purposes have been reviewed in detail by French-McCay (2009). Assumed values of time to recovery (t_{rec}) for vegetation or species important for the structure of a habitat, are specific to habitat type and are based on experiences from observations of natural recovery following disturbance (including spills) and from habitat creation projects. Time for recovery of benthic invertebrates to 99% of function/pre-spill situation is shown in table Table 3.3 (Brude et al. 2015).

RDF_{SH} is calculated using the generic calculation for each ESI ranking. The unit is "kilometeryears". Usually no distinction is possible between lag and restoration

Table 3.3 Restoration -times in shoreline types—vegetation and invertebrate communities (time to 99% of pre-spill function)

Habitat type (ESI class)	Vegetation or structure (years)	Invertebrates (years)
Rocky shore (1 and 8) Exposed rocky platforms (2) Fine grained sand beaches (3) Coarse grained sand beaches (4) Mixed sand and gravel beaches (5) Gravel beaches and rip rap-structures (6) Exposed tidal flats (7 and 9)	–	3
Wetland: Emergent Marsh (10A, 10B)	15	5
Wetland: Swamp (10C, 10D)	20	5

phases in recovery studies from spills (as in French-McCay 2009), meaning that implementation of observed recovery times as restoration time in ERA Acute can be conservative when including also a lag-time before recovery can start.

$$RDF_{SH,SF} = \frac{Imp_{r,month} \times t_{imp}}{2} + (Imp_{r,month} \times t_{lag}) + \frac{Imp_{r,month} \times t_{res}}{2} \tag{3.9}$$

- t_{imp}: *Impact time*. Time until full impact is observed. This value is set to 1 year as most acute impacts are assumed to be apparent after 1 reproductive year cycle.
- t_{lag}: *Lag-time*. Time until contamination has been reduced sufficiently for restoration to begin.
- $t_{res:}$ *Restoration time*. The time from restoration starts until the population/community is restored to a pre-defined level of its pre-spill status or equivalent threshold.
- *Imp* is impacted length of coastline (km).

3.5 Water Column Compartment

3.5.1 Impact Modelling

Two different approaches are developed for ERA Acute water column impact calculations and are described in the development report by Brönner et al. (2015).

3.5.1.1 Time-Averaged THC-Max

One alternative calculation uses input of "THC_{max}" (total hydrocarbon concentration) from the oil drift simulations to calculate p_{let} in each cell, using an SSD curve (Nilsen et al. 2006). In OSCAR, this representative THC-concentration is calculated throughout the oil drift simulations, the highest THC-concentration from any of the water layers is recorded at each time-step and the final value is the average of these (time-averaged "THC_{max}"). Similar values from other reliable oil spill models may also be used, however differences in how the inputs are calculated must be observed.

The concentration is entered into a dose-response curve (Species Sensitivity Distribution (SSD)) proposed by Nilsen et al. (2006) for use in EIF Acute (Spikkerud et al. 2006). The SSD is based on a dataset compiled by the National Research Council of the National Academies (2005).

The SSD curve has a 5% effect level (LC5) of 58 ppb THC for dispersed oil in sensitive species, and a LC50 value of 193 ppb. p_{let} in each simulation and each grid cell i is given as:

$$p_{let,WC,i,sim} = \Phi\left(\left(\frac{lnx - ln193)}{0.73}\right), \mu, \sigma\right) \tag{3.10}$$

where:

- Φ: cumulative normal distribution function: with $\mu = 0$ and $\sigma = 1$
- x: target THC concentration.

3.5.1.2 Externally Calculated Lethal Fraction

In addition to the complexity of a three-dimensional compartment and varying composition of the spilled oil due to weathering processes, the main challenges for computing the impact of oil to water column organisms include the temporal variation in toxicity of the oil, as well as temporal and spatial variations in oil concentrations due to transport and weathering. This is better reflected when the potential mortality accumulates during the course of the oil drift simulations and requires access to an oil drift model that calculates an accumulated fraction of the eggs/larvae that are killed. This fraction is then used directly as p_{let}. ERA Acute allows for the results of advanced oil spill models that calculate the eggs/larvae fraction lost to be entered into the model but does not require it. Below, a description is given on how the oil spill model OSCAR calculates this potential fraction killed.

Oil in the water column is partitioned between dispersed oil droplets and water-soluble fractions (dissolved oil components). For the dissolved phase, the "fraction killed" per cell is accumulated over the time steps of the simulation using a Quantitative Structure-Activity Relationship (QSAR) between toxicity and the composition and amount of the dissolved hydrocarbons at the time step. Choice of reference oil is therefore an important driver in the result, as different oils have different hydrocarbon group compositions. Based on their molecular structure, the toxicity of the dissolved phase is calculated and the toxicity of the mix is a function of the composition of the hydrocarbon mix, as known from QSAR theory used in predictive toxicology (French-McCay 2002). This approach uses the octanol-water partitioning coefficient (K_{OW}) and the corresponding narcotic effect as the endpoint.

Time- averaged concentration and the corresponding mean composition are calculated for the actual exposure times (τ) in subsequent 96-hour periods. The exposure time is defined as the time when dissolved oil is present at a concentration > 0 in the given 96-hour period (Johansen et al. 2005).

Each component group has an LC50 value and at each time-step (in each cell) the corresponding potential lethality of the mix is calculated by a modification of Eq. 3.11 (French-McCay 2002).

$$LC50_{mix} = 1 \Big/ \sum \frac{F_j}{LC50_j} \tag{3.11}$$

where F is the fraction of the component j in the mix. The modification adjusts for exposure time (τ) by the following equation (Johansen et al. 2005);

$$LC50(\tau) = LC50_{\infty}\left[1 - \exp(-\varepsilon\tau)\right] \tag{3.12}$$

$LC50_{\infty}$ is the intrinsic toxicity value, which is assumed to correspond to 96 h LC50 values for each component group (Johansen et al. 2005). ε is a coefficient which expresses the exposure time dependency of the toxicity. It depends on the KOW for the given component by the equation log $\varepsilon = 1.47–0.414$ log KOW (French-McCay 2002).

The dose-response curve used is a log-normal Species Sensitivity Distribution (SSD) curve developed by Nilsen et al. (2006) (logarithmic SD = 0.32). The LC5 value derived from the SSD curve is used to represent LC50 for a particularly sensitive species (5th percentile most sensitive), which is used as the effect limit for dissolved components.

Based on the QSARs, the Critical Body Residue (CBR) is calculated by CBRj = BCFj × LC50j for each component group j, Bioconcentration Factor (BCF) is related to KOW (Brönner and Nordtug 2015). To calculate the actual body residue at each time step for each component, the body concentration is a result of uptake and elimination. The uptake rate is proportional to the environmental concentration C_A, while the elimination rate is proportional to the body concentration (body residue) C_B. The uptake rate is related to the size of the organism (Hendriks et al. 2001) and the lipophilic properties of the compounds which are related to the octanol/water partitioning constant (Log Kow). See Brönner and Nordtug (2015) for equations OSCAR uses to calculate this, referring to De Hoop et al. (2013) and McCarty and Mackay (1993). From the calculated body residue (CB) at the given timestep, a potential mortality is calculated by the SSD curve developed by Nilsen et al. (2006) and implemented as:

$$\text{Potential mortality, } P = (x, 0, \sigma)$$

where Φ is the cumulative normal distribution with argument x, mean value 0 and standard deviation (slope) σ, $x = \log(C_B/\text{CBR})$ or log $(\Sigma(C_{B,j}/\text{CBR}_j)$ (where j is component) and standard deviation is = 0.32. This dose-response curve is used to compute potential mortality in each grid cell at each time-step. The accumulated maximum mortality over all time steps is reported as “fraction killed” in the cell which is then used as input to ERA Acute. The maximum is a maximum of the whole water column, which may be conservative in some water layers.

This second approach in ERA Acute involves access to detailed modelling of input of potential mortality and an oil spill model that has composition information on component groups. It bears some similarities with calculation of mortalities of early life stages of fish in SYMBIOSES (SYsteM for BIOlogy-based asSESsments), which consists of several coupled models where OSCAR provides the oil spill input on component composition at each time step to LARMOD, which in turn calculates toxicity using chemical uptake kinetics and elimination rates for a given life stage. The fish ecotoxicology module calculates mortality assuming additive effects between mortalities caused by individual pseudo-components (Carroll et al. 2014, 2018).

3.5.2 Time Factors and Recovery Modelling

In the water column a lag time is not assumed, as the impact will occur within the annual spawning cycle and the oil in the water column will not be present the following year as a residual contamination.

The larvae loss is calculated as described in Sect. 3.6.1, as the maximum fraction killed summed up over all cells in the simulation to a total larval loss for that spill simulation. The total oil-induced impact (sum of all cells) (Imp_{total}) on fish eggs and larvae, representing the year class 0, is input data as a larvae loss to the restoration model, which expresses impact on the reproductive unit (spawning stock development). Two runs of the *global fish restoration model* are made, with and without oil impact to eggs/larvae, using basic parameters of population biology to calculate expected recruitment (E_{Recr}) with and without oil, relative to the average recruitment ($\text{Recr}_{\text{Average}}$). This is then used to calculate the time until the fish spawning stock is back to pre-spill status (See Brönner et al. 2015 for more detail).

Recruitment of juvenile fish from spawning product to the adult spawning stock is the result of many complex and interacting factors of both biological and oceanographic origin, and the fluctuation of recruitment success is high, resulting in strong and weak year classes. Two of the best examined fish species worldwide; Barents Sea cod (*Gadus morhua*) and capelin (*Mallotus villosus*) are used as representative for a long-lived (cod) and a short-lived (capelin) species. Research of spawning and abundance of juveniles of these two species shows that typical mortality rates in pelagic spawners are well above 99% already at the end of the larval stage (4–5 months) (Marshall et al. 2006; Eriksen et al. 2009; Huse and Gjøsæter 1997). For 0-group and juvenile fish, natural mortality continues to be high, or very high and are strongly fluctuating.

ERA Acute uses a “gate model” in restoration modeling. The gate specifies the number of surviving larvae to become recruits, rather than inducing an annual mortality. The parameter *Critical density* (default 5%) expresses the threshold for when a direct relationship is modelled between the size of the spawning stock and recruitment.

If the analyzed fish stock is above critical density, recruitment is fully independent of the size of the spawning stock (Eq. 3.13). If the analyzed fish stock is below critical density the spawning success may be too low for adequate recruitment. The model then calculates the expected recruitment relative to current spawning stock size ($\text{SS}_{\text{current}}$) and the long-term average spawning stock ($\text{SS}_{\text{average}}$) (Eq. 3.14):

$$E_{recr} = Recr_{average} \tag{3.13}$$

$$E_{recr} = Recr_{average} \times \frac{SS_{current}}{0.05} \times SS_{average}. \tag{3.14}$$

Critical oil mortality (%) represents the threshold mortality of eggs and larvae and defines the level of conservatism for the relationship between larvae mortality and reduced recruitment. If Imp_{total} < Critical oil mortality, the "gate model" is used (Brönner et al. 2015): Modelled natural survival up until recruitment is the reference level against which oil impact on eggs and larvae is measured (scientifically most valid approach). If Imp_{total}> Critical oil mortality, oil-induced mortality of larvae equals reduction in recruitment. Critical oil mortality can be set low for added conservativity.

ERA Acute, using the gate model, calculates N_i as the spawning stock size without oil impact and $N_{oil,i}$ is spawning stock size where the population in the first year was impacted by oil-induced mortality.

Recruitment modification: In the gate model, annual recruitment (E) is simulated as a modification of the potential recruitment weight (W) using probabilities (P) of periods of favorable and unfavorable conditions.

The expected value of the recruitment weight modification (E(W)) in a randomly chosen year is:

$$\begin{aligned} E(W) =&[P_{unfavorable} * E(W)_{favorable}] + [P_{shift} * E(W)_{shift}] \\ &+ [P_{favorable} * E(W)_{favorable}] \end{aligned} \tag{3.15}$$

The simulated recruitment is calculated as:

$$R_1 = 1000 * [W1/E(W)],\ R_2 = 1000 * [W2/E(W)], \ldots, R_k = 1000 * [Wk/E(W)] \tag{3.16}$$

Population model: In the population model:

X_t represents the number of spawning adults in year t. Average abundance of the spawning stock is denoted E(X). Three parameters are needed in the iteration equation, and these values are different for different species depending on whether they are long-lived (cod) or short-lived (capelin) (Table 3.4):

- Annual natural mortality in percentage (m),
- age at recruitment (tr),
- age at sexual maturity (tm).

Table 3.4 Input data to the Population model used in ERA Acute for long-lived and short-lived species (Table from Brönner et al. 2015)

Parameter	Long-lived species	Short-lived species
Annual mortality of immatures (%)	20	40
Annual mortality of matures (%)	20	40
Age at recruitment	3	1
Age at first spawning	8	5
Maximum age	25	5

The average number of first year spawners is: $E(R) \times [(1–m)^{tm-tr}]$

Average, natural mortality of adults is: $X \times m$.

In a sustainable population, the gain (new recruits) and loss of individuals (natural mortality of adults) must balance each other, and we have that $E(R) \times [(1–m)^{tm-tr}] = E(X) \times m$.

The average abundance of adults (E(X)) corresponding to an average number of E(R) recruits is therefore: $E(X) = E(R) \times [(1–m)^{tm-tr}/m]$.

Because of the stochastic nature of recruitment, the abundance of the spawning stock at time $t + 1$ will fluctuate around this expected number of spawners according to the iteration equation:

$$X_{t+1} = [X_t \times (1 - m)] + \left[R_{t+1-(tm-tr)]} \times [(1 - m)^{tm-tr}]\right]$$

For the interested reader, the full algorithm programming guide containing 333 functions and interdependencies in given in Appendix C of Brönner et al. (2015).

Resource damage factor in the water column, RDF_{WC} is expressed as *spawning stock reduction years* (Eq. 3.17) and is calculated as sum of difference in % in the modelled spawning stock size with and without oil-induced mortality in years where difference exceeds 1%. This means that 99% of the undisturbed state is used as a threshold for the resource impact calculation, although in a fluctuating environment, natural variation will oscillate with much higher amplitude than 1%.

$$RDF_{WC} = 100 \sum_i \frac{N_i}{N_{oil,i}}, \forall_i \frac{N_i}{N_{oil,i}} > 0.01 \tag{3.17}$$

where:

- N_i is spawning stock size without oil impact.
- $N_{oil,i}$ is spawning stock size where the population in the first year was impacted by oil-induced mortality.

3.6 Seafloor Compartment Functions

3.6.1 Impact Modelling

The seafloor is divided into the sub-compartments hard bottom and soft bottom (sediment) and feeding modes are used to determine exposure route(s) for the species groups on several soft sediment substrate types (Stephansen et al. 2015). The main impact to sediment *infauna* is via exposure through interstitial water (IW) and to hard-bottom and soft substrate *epifauna* through water column using the same impact modelling as in the water column compartment. The additive effect of ingestion (Ing) is added for *epifaunal* and *infaunal* deposit feeders, where exposure is through hydrocarbons leached into gut water.

Equilibrium Partitioning Theory (EqP) is used to determine exposure to sediment-dwelling organisms (Schwartz et al. 1990; Di Toro et al. 1991; EPA 2008). With input of THC in sediment from oil drift modelling in kg/m^2, ERA Acute first calculates the concentration of THC (C_{THC}) in the sediment in ppb, using mixing depth, dry density and water content of the soft substrate type, and then calculates the partitioning of THC between sediment-bound (THC_{sed}) and bioavailable interstitial water (THC_{IW})-using inputs of octanol-water coefficients (K_{OW}) and total organic carbon (TOC) to calculate organic carbon/water partition (K_{OC}). The concentration in IW (C_{IW}) determines exposure to *infauna*.

$$C_{THC,sed,cell,sim}\left(\frac{\text{mg}}{\text{kg}}\right) = \frac{THC_{sed,cell,sim}\left(\frac{\text{kg}}{\text{m}^2}\right) \times 10^6\left(\frac{\text{mg}}{\text{g}}\right) \times \frac{1}{BDepth(m)} \times (1 - \text{WatC})}{DryDens\left(\frac{kg}{m^3}\right)}$$

where:

- Mixing depth (BDepth): Depth of bioturbated layer in m (meters). Used to derive THC concentrations in sediments from THC/m^2
- WatC: Water content of sediment = porosity (void volume) (given as Volume fraction 0–1 where 1 = 100%)
- DryDens: Density of dry weight fraction of sediment.

$$Log_{10}K_{OC} = 0.00028 + 0.983 \times (Log_{10}K_{OW})(\text{Di Toro et al.}1991)$$

where

- TOC: Concentration of TOC in habitat, is sediment (as fraction) = foc

The concentration of THC in the sediment interstitial water is calculated as:

$THC_{IW,cell,sim} = THC_{sed,cell,sim}/(foc \times Koc)$ (derived from EPA 2008 and Di Toro et al. 1991).

For deposit feeders that ingest sediment particles, partitioning between THC_{sed} and exposure in gut water (THC_{Ing}) is determined using calculated bioconcentration factors (BCF) to determine Biota-to Sediment Accumulation factors (BSAF) (Kraaij et al. 2002; (Klif) Klima- og forurensningsdirektoratet 2011).

$$\text{BSAF} = \text{BCF}/(K_{oc} \times f_{oc})$$

where: Log BCF = 0.85 × Log K_{OW} − 0.70

(See more information how this is used in Stephansen et al. 2015). The calculated exposure concentration THC_{IW} or THC_{Ing} is entered into the SSD-curve by Nilsen et al. (2006) to calculate $plet_{IW}$ and $plet_{Ing}$. For *epifauna*, e.g. corals or sponges THC_{WC} is currently used directly to determine $plet_{WC,SF}$ using an SSD-curve derived by Nilsen et al. 2006, pending improved stochastic modelling of time-averaged mortality directly in the *lower* water column using the preferred method for water column resources (see 3.6.1).

Species that ingest sediment particles are exposed both externally ($plet_{IW}$ or $plet_{WC,SF}$) and with added lethality from $plet_{Ing}$. Seven feeding modes are identified based on biological criteria, which are assigned to four essential exposure mode combinations: Exposure through water column (WC) (*epifauna*) or IW (*infauna*) and any of these with ingestion (Ing) for deposit feeders.

VEC data are prepared either as single-species data or substrate-based data community data with a feeding mode. If accurate data for distributions of feeding modes within a community can be found, it is possible to assign community VECs with a combination of fractions of feeding modes in a *community* contributing to the calculation (See Stephansen et al. 2015). For species that are partially *infaunal*, partially *epifaunal*, such as e.g. seapens, these may be ascribed an additive effect of both WC and IW exposure by using both modes to define exposure. The calculator will then summarize the two p_{let}-values to an additive effect.

3.6.2 *Time Factors and Recovery Modelling*

In the seafloor compartment, the time factors are included in the impact calculation for each cell and simulation before the results are summarized and statistics are presented. Impact time, t_{imp} is default set to 1 year to cover an annual cycle. For soft substrates, the lag-time, $t_{lag,sed}$ is set to 0 in the current soft substrate implementation, assuming that restoration begins next reproductive cycle.

Restoration time, t_{res} in soft substrates are calculated by a linear relationship (Olsgård and Gray 1995) implemented as Eq. 3.19, between the amount of oil in the sediment (THC_{sed}) above a threshold value ($THC_{threshold,sed}$) (currently 50 ppm, Renaud et al. 2008) and the expected maximum concentration of THC resulting from sedimentation of oil from an accidental release ($THC_{benchmark\text{-}max,sed}$). (currently 1000 ppm (Olsgård and Gray 1995). The average value of 20 years found in literature search (Renaud et al. 2008) is based on data from the North Sea (for which sandy sediments are the "standard" substrate). For VECs (substrate communities) with different recovery times than the average value of 20 years, a restoration time-modifying sensitivity factor (SF) is used to calculate t_{res} (Eq. 3.19). The value of SF is currently proposed to be calculated as the ratio of the TOC-content of the substrate relative to the TOC-content of the sand substrate for which 20 years was found to be the restoration time ("standard-substrate") (Eq. 3.18, in Stephansen and Bjørgesæter 2018). RDF is calculated from the general Eq. 3.9 shared with Shoreline.

$$SF_{substr} = TOC_{substr}/TOC_{std.substr} \tag{3.18}$$

$$t_{res,sed} = \frac{(THC_{sed} - THC_{threshold,sed})}{THC_{benchmark-max,sed}} \times 20 \times SF_{substr} \quad (3.19)$$

For hard-bottom communities, such as corals etc., a significant number of years may pass before any re-growth is seen. (Fisher et al. 2014; White et al. 2012; Hsing et al. 2013). A lag-time before recovery commences (t_{lag}) and the restoration time (t_{res}) are given in the form of input tables as functions of the impact magnitude to the coral. (See table in Stephansen et al. 2015; Background Report 6 Seafloor Compartment ERA Acute 2015).

3.7 Summarizing Impacts in Cells to Scenarios and DSHAs

As explained in Chap. 1, the smallest unit of calculations for a VEC is in each grid cell for each single oil drift simulation (Fig. 1.6).

From simulation and cell level, results can be analyzed to the total average risk for the spill scenario and DSHA. Figure 3.3 gives an overview of the main components and the available endpoints per cell, in single simulations and eventually in multi-scenario cases. Results presented in Fig. 3.3 show how the expected impacts (based on averages or weighted impacts) are calculated, where scenario probabilities and incident frequencies are included at certain steps in the calculations.

In addition to the overall summarized results, using the single simulation results in cells ($I_{VEC,sim,cell}$ in Fig. 3.3), a range of statistical results can be presented, e.g. percentile-values, maximum values, probabilities of impacts in ranges etc. All time factors are recorded as outputs and are available for separate statistics of total time to recovery. Although ERA Acute uses continuous impact and restoration functions for improved resolution over MIRA (NOROG 2007), grouping results in impact or time-factor ranges is useful, and can be plotted in risk matrices against scenario probabilities or DSHA frequencies. Calculations in single cells and simulations (upper section, Fig. 3.3) provide the most detailed options for result analysis of scenario results. Summary steps from initial calculation of impact in a cell for a simulation, up to the sum of total expected impact for a DSHA (lower section) gives results for multi-scenario DSHAs and cases. The illustration in Fig. 3.3 shows that many levels of calculations may be extracted and presented.

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